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Authors: John T R Liddon; Michael J James; Aimee K Clarke; Peter O'Brien; Richard J K Taylor; William Paul Unsworth

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Catalyst-driven scaffold diversity: selective synthesis of spirocycles, carbazoles and quinolines from indolyl ynones

John T. R. Liddon, Michael J. James, Aimee K. Clarke, Peter O'Brien, Richard J. K. Taylor* and William P. Unsworth*

Abstract: Medicinally relevant spirocyclic indolenines, carbazoles and quinolines can each be directly synthesised selectively from common indolyl ynone starting materials by catalyst variation. The high yielding, divergent reactions all proceed via an initial dearomatising spirocyclisation reaction to generate an intermediate vinyl metal species which then rearranges selectively by careful choice of catalyst and reaction conditions.

The synthesis of structurally diverse compounds is central to the discovery of pharmaceutical lead compounds.¹ However, the formation of distinct compound sets usually requires multiple synthetic routes, which is time-consuming and labour-intensive; therefore strategies capable of selectively forming multiple products from common starting materials are of high value. The concept underpinning our approach is the formation of a common reactive intermediate (from a simple, inexpensive starting material) which depending on the catalyst used can rearrange into different scaffolds (e.g. spirocycles, aromatics and heterocycles/carbocycles, Figure 1). This approach has the potential to significantly streamline existing synthetic methods, and lead to a broader understanding of catalysis and reaction mechanisms. Although there have been numerous examples of catalyst variation leading to different products in recent years,^{2,3} such methods have mainly focused on the formation of products with similar frameworks (e.g. redox isomers, regioisomers or stereoisomers). In this work, our aim was to develop a series of divergent processes capable of selectively delivering multiple products with the level of scaffold diversity outlined in Figure 1.

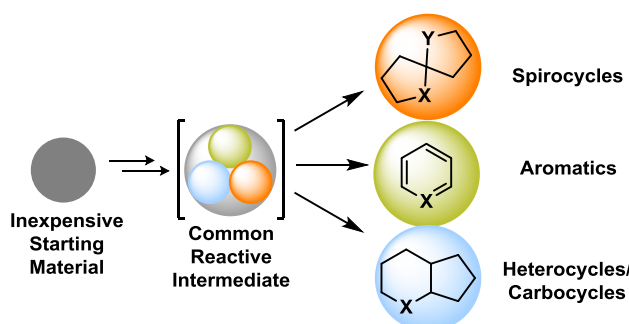
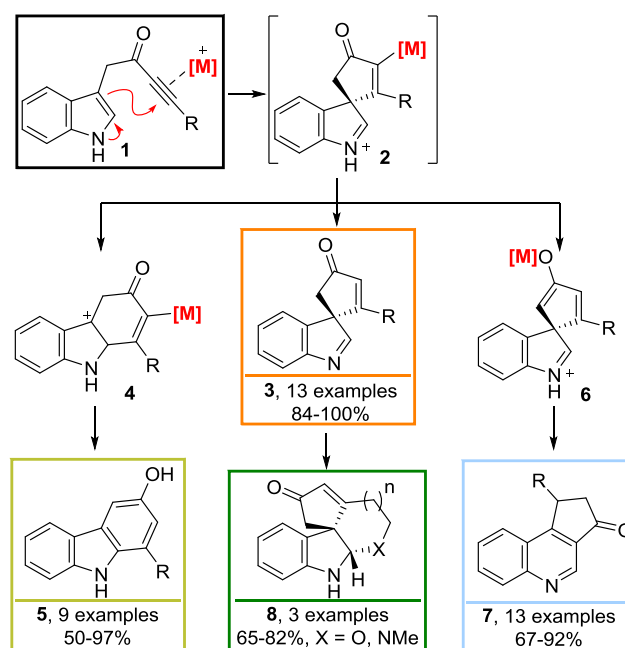


Figure 1. Catalyst-driven scaffold diversity.

To demonstrate the synthetic potential of our scaffold-diversity approach we chose to explore the formation and

subsequent reaction of spirocyclic vinyl metal intermediates of the form **2** (Scheme 1). Previous work in our research group has demonstrated that the dearomatising spirocyclisation⁴ of ynones **1** into spirocyclic indolenines **3** can be catalysed by AgOTf, with a vinyl silver intermediate (**2**, [M] = Ag) a likely intermediate.⁵ A key design feature of our strategy was the idea that varying the catalyst would alter the nature and reactivity of the vinyl metal intermediate **2** in a programmable way, such that alternative products could be formed via different rearrangement reactions. Herein we report the successful realisation of this approach. Notably, by judicious choice of catalyst, simple, inexpensive ynone starting materials **1** can be converted into spirocyclic indolenines⁶ **3** using Ag(I), carbazoles **5** using Au(I), and quinolines **7** using Ag(I)/Al(III), in high yield, each via a simple, catalytic and atom-economical process. Furthermore, in suitable cases, tetracyclic scaffolds **8** can be formed with complete diastereoselectivity, via a telescoped spirocyclisation/nucleophilic addition sequence, which was also performed using a chiral Ag(I) salt to furnish an enantiopure product.



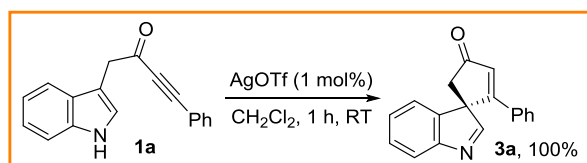
Scheme 1. Divergent synthesis of spirocycles **3**, carbazoles **5**, quinolines **7** and tetracyclic scaffolds **8** from indolyl ynones **1**.

The spirocyclisation of **1a** using AgOTf formed indolenine **3a** in quantitative yield (Scheme 2);⁵ the mild reaction conditions are believed to play a key role in this process, stabilising the spirocycle with respect to further reactions. However, in the proposed scaffold diversity approach, in which the synthesis of carbazole **5a** was an initial goal, the challenge was to deliberately promote 1,2-migration⁷ in a controlled manner.⁸ A

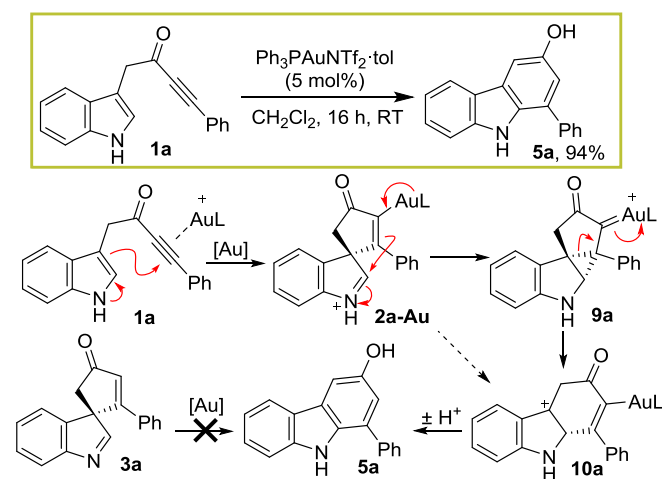
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$\text{Ph}_3\text{PAuNTf}_2\cdot\text{tol}$ catalyst was chosen based on the prediction that the π -acidic gold(I) catalyst would effectively promote the initial spirocyclisation reaction and that the intermediate vinyl gold species (**2a-Au**) would be prone to 1,2-migration, based on known reactivity of related vinyl gold and gold carbenoid species.⁹ This idea was validated (94% yield of **5a**), with a likely reaction mechanism depicted in Scheme 3; the ring enlargement is believed to proceed either via cyclopropane intermediate **9a**, or a via a direct 1,2-migration reaction (**2a-Au** \rightarrow **10a**) based on related precedent.^{7,9} The importance of the vinyl gold intermediate **2a-Au** in the 1,2-migration is evidenced by the fact that no reaction takes place when spirocycle **3a** is treated with $\text{Ph}_3\text{PAuNTf}_2\cdot\text{tol}$ under the same conditions.



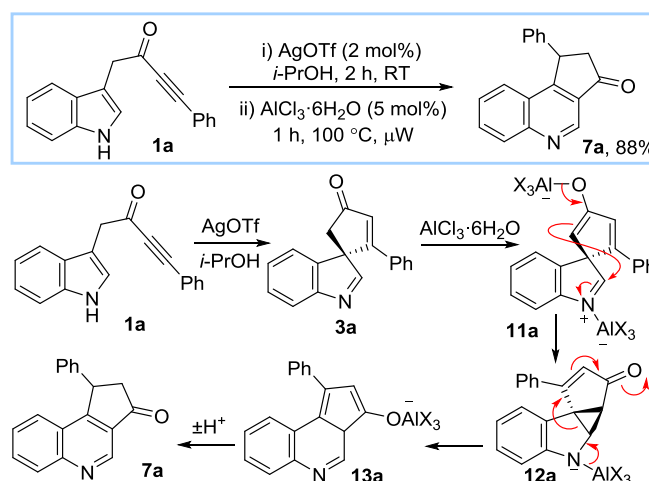
Scheme 2. Formation of spirocyclic indolenine **3a**



Scheme 3. Formation of carbazole **5a**; [Au] = $\text{Ph}_3\text{PAuNTf}_2\cdot\text{tol}$, L = ligand

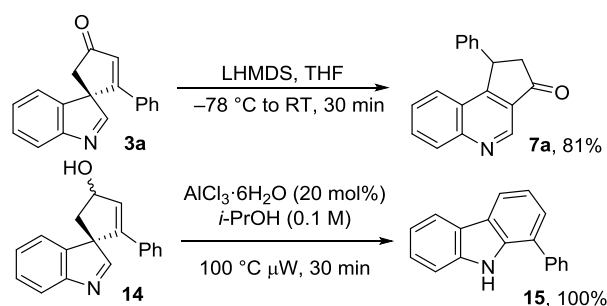
We next examined whether we could initiate an alternative rearrangement commencing from ynone **1a**, by seeking to promote cyclopropanation of an enolate from the less substituted branch of the cyclopentenone; more oxophilic catalysts were chosen for this task, as it was thought that they would better promote the necessary enolate formation. We were unable to uncover a catalyst that could successfully initiate spirocyclisation and subsequent rearrangement on its own. However, first performing the spirocyclisation using 2 mol% of AgOTf as catalyst in *iso*-propanol, followed by the addition of 5 mol% of $\text{AlCl}_3\cdot 6\text{H}_2\text{O}$ and subsequent heating in a microwave gave quinoline **7a** in high yield (Scheme 4).¹⁰ Following Ag(I)-mediated spirocyclisation, it is thought that the Al(III) catalyst promotes enolate formation and subsequent cyclopropanation to

form **12a**, which can then fragment to form **13a** and aromatise to give quinoline **7a** (either by simple proton shuttling, or via a series of 1,5-sigmatropic H-transfer reactions).



Scheme 4. Formation of quinoline **7a**; X = Cl or *i*-PrO

Supporting evidence for this unprecedented rearrangement was obtained: treatment of spirocycle **3a** with LHMDS in THF (*i.e.* conditions which almost certainly would result in enolate formation) also led to the formation of quinoline **7a**, in 81% yield. Furthermore, the importance of the carbonyl group was shown by the fact that treatment of known cyclopentenol **14**¹¹ with $\text{AlCl}_3\cdot 6\text{H}_2\text{O}$ did not result in quinoline formation. Instead, 1,2-migration of the alkenyl group took place, furnishing carbazole **15** following tautomerisation and dehydration (Scheme 5).



Scheme 5. Base-mediated formation of quinoline **7a** and the contrasting reactivity of spirocyclic cyclopentenol **14**.

To probe the scope of all three reaction manifolds, various functionalised indole-tethered ynones **1a–1m** were prepared, substituted in several positions with electron-rich and electron-poor aromatics, alkyl substituents, *O*- and *N*-protected alkyl groups and PhS.¹² First, using the AgOTf-mediated spirocyclisation methodology, substrates **1a–1m** were cleanly converted into the corresponding spirocyclic indolenines **3a–3m**, all in excellent yields (Table 1, Conditions A).

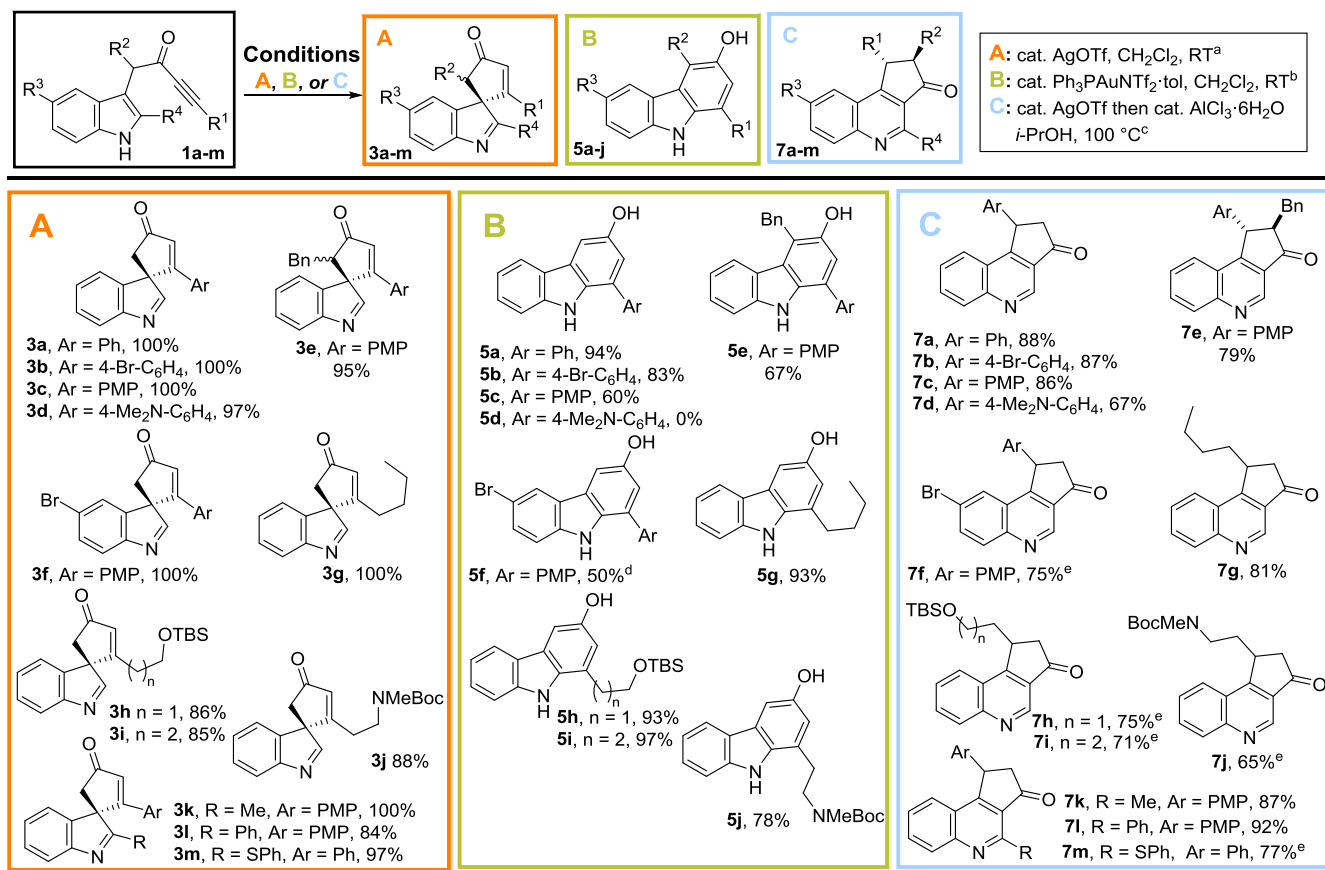


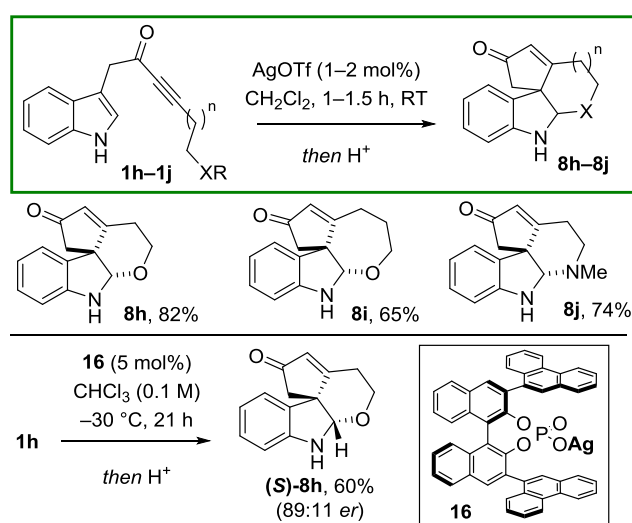
Table 1. ^a 1 mol% AgOTf in CH₂Cl₂ (0.1 M) at RT for 0.1–3.5 h; ^b 2–5 mol% Ph₃PAuNTf₂-tol in CH₂Cl₂ (0.1 M) at RT for 7–18 h; ^c 1 mol% AgOTf in *i*-PrOH (0.1 M) at RT for 1–3 h, then 5–10 mol% AlCl₃·6H₂O at 100 °C μ W for 1–2 h; ^d Reaction performed in toluene; ^e 1 mol% AgOTf in CH₂Cl₂ (0.1 M) at RT for 1–3 h, then solvent swap for *i*-PrOH (0.1 M) then 5–10 mol% AlCl₃·6H₂O at 100 °C μ W for 1–2 h. PMP = *para*-methoxyphenyl

The Ph₃PAuNTf₂-tol mediated carbazole forming reaction was similarly broad in scope (Table 1, Conditions B); some reactions were less efficient than the analogous spirocycle formations, and ynone **1d** did not produce any of the desired product (instead stalling at the formation **3d**), but the majority of the carbazole products **5a–j** were isolated in very good yields.¹³

Finally, the quinoline forming reaction sequence was also found to be very general (Table 1, Conditions C). For ynone **1a–1e**, **1g**, **1k–1l**, the sequential AgOTf spirocyclisation and AlCl₃·6H₂O mediated rearrangement steps could both be performed in *i*-PrOH in one-pot as described, whereas for ynone with more sensitive functional groups (**1f**, **1h**, **1i**, **1j**, **1m**), the process benefited from a solvent swap, with the spirocyclisation first being performed in CH₂Cl₂ before concentration and addition of *i*-PrOH prior to the AlCl₃·6H₂O step. The AlCl₃·6H₂O reactions were typically performed under microwave irradiation at 100 °C, but it was also shown to proceed well, on gram scale, with conventional heating, albeit with a longer reaction time being required.¹⁴ The structure of quinoline **7f** was confirmed by X-ray crystallography.¹⁵

Another strand of scaffold diversity starting from more functionalised ynone **1h–1j** was briefly explored. Tetracyclic scaffolds **8h–j**, equipped with additional complexity, were easily obtained following reaction of ynone **1h–1j** with AgOTf and subsequent acid-mediated protecting group cleavage in one-pot (Scheme 6, see Supporting Information for details).¹⁶ The

tetracycles were formed as the single diastereoisomers shown, and in addition, (**S**)-**8h** was prepared in enantioenriched form (89:11 *er*) by utilising (*R*)-CPA silver(I) salt **16** in place of AgOTf.¹⁷ The *er* of (**S**)-**8h** could be increased to ~100:0 by recrystallisation from ethanol and its structure was confirmed by X-ray crystallography (see Supporting Information).¹⁵



Scheme 6. One-pot spirocyclisation/trapping to form tetracycles **8h–8j**.

In summary, readily available indolyl ynones have been shown to be versatile starting materials for the synthesis of spirocyclic indolenines **3a–m**, carbazoles **5a–j**, quinolines **7a–m** and tetracyclic compounds **8h–j** using a catalyst-driven scaffold diversity approach. The reactions are typically high yielding, work on a wide range of indolyl ynone substrates, are operationally simple and can all be performed with no effort to exclude air or moisture. All of the procedures are thought to proceed via an initial dearomatising spirocyclisation to form a key vinyl metal intermediate before diverging at this point depending on the nature of the catalyst used. The synthetic methods are expected to be of value both in target synthesis projects¹⁸ and to enable the rapid generation of compound libraries for biological screening.

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Keywords: Catalysis • Diversity • Spirocycles • Carbazoles • Quinolines

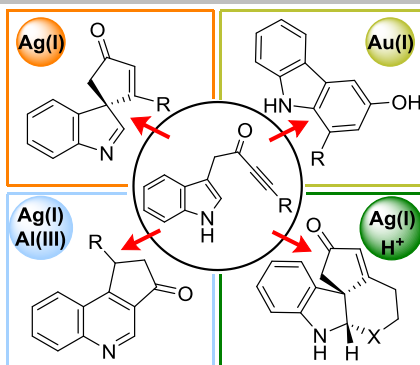
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Page No. – Page No.

Catalyst-driven scaffold diversity: selective synthesis of spirocycles, carbazoles and quinolines from indolyl ynones

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